Electrical Resistivity Surveys to Define Distributions of Silt and Clay Layers near the San Pedro River, Sierra Vista Subwatershed of the Upper San Pedro River Basin

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Abstract

Ground-water flow to the ecologically important San Pedro River in southeastern Arizona is restricted by the distribution of underlying silt and clay layers. A better understanding of the distribution of these layers is needed to determine the effects of ground-water withdrawals on river flow. Results from 13 electrical resistivity transects, 300 to 1,580 meters in length, were used to map the distribution of silt and clay layers to depths of 50 to 100 meters along a 25-kilometer reach of the river. Some of the transects were near piezometers, and the resistivity results were compared with borehole and water-level data. Distinct distributions of silt and clay were identified along three reaches of the river. The northern reach has no significant silt and clay layers, and ground water flows relatively unrestricted to discharge at the river. The middle reach has a significant silt and clay layer that effectively isolates the river and ground water in the Quaternary alluvium from a deep ground-water flow system in the basin fill. The southern reach has significant silt and clay layers that include interlayered sand and gravel that transmit a small amount of ground water to the Quaternary alluvium and river.

Introduction

Ground-water withdrawals in the upper San Pedro River Basin of southeastern Arizona intercept ground-water flow that sustains the ecologically important San Pedro Riparian National Conservation Area (SPRNCA; fig. 1). The basin is undergoing development, and demands for use of ground-water supplies will likely increase. Water managers want to minimize impacts to streamflow and the riparian area. Knowledge of hydraulic interactions between the alluvial aquifer and the river are key to understanding how ground-water withdrawals affect water availability in the SPRNCA. These interactions are controlled in part by distributions of hydraulic properties in the aquifer. Specifically, low-permeability layers of silt and clay near the river control the transmission of ground water to the river and riparian vegetation. Where these layers exist beneath the river, little ground-water flow occurs between the aquifer and the river. Mapping the distribution of these low-permeability layers will help water managers determine where ground-water withdrawals could reduce ground-water flow to the river and where to place artificial recharge facilities for streamflow enhancement.

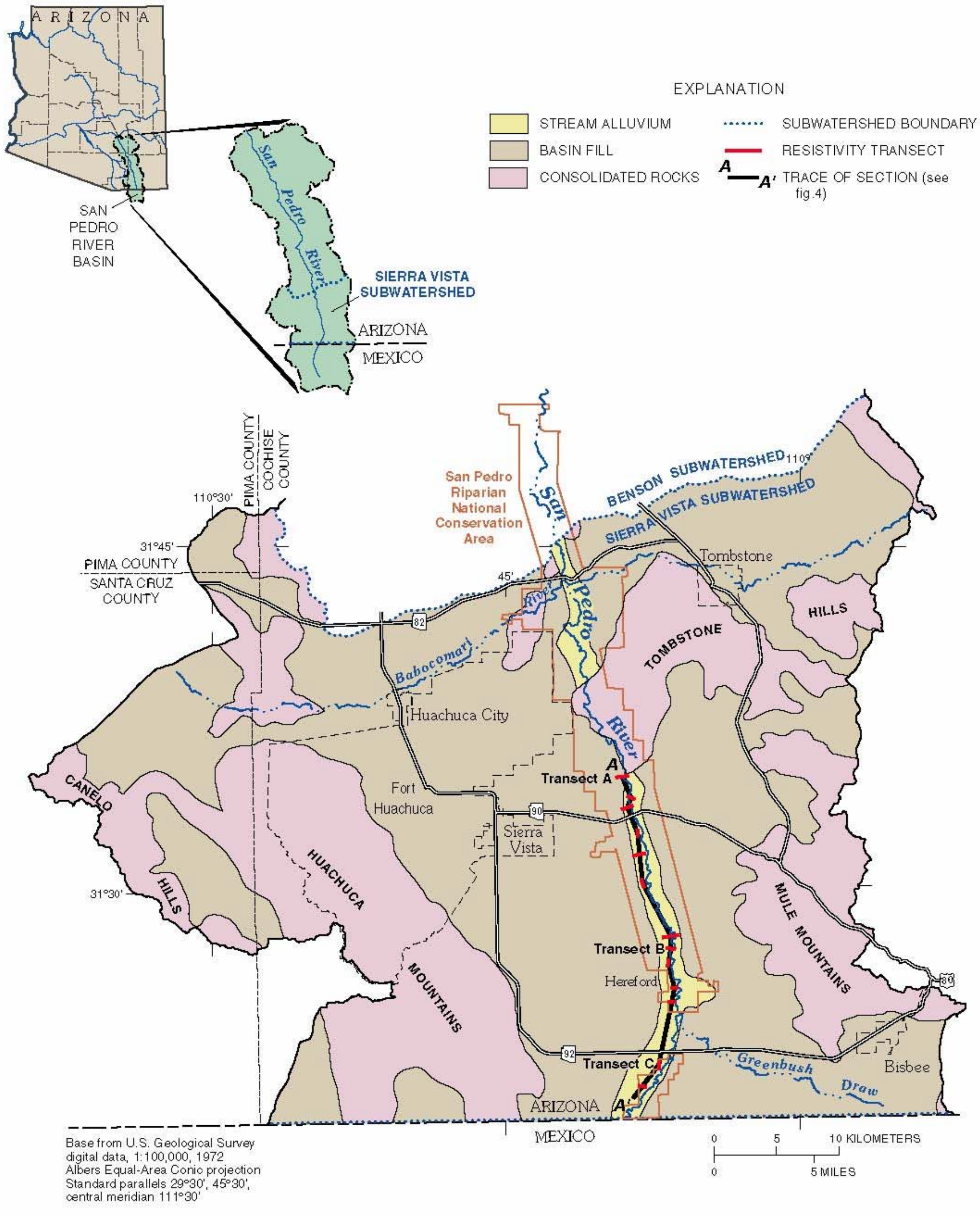

Figure 1. Location of study area and resistivity transects near the San Pedro River, Arizona.

Methods

Direct-current resistivity surveys were used to map the distribution of electrically conductive silt and clay layers to depths of 50 to 100 m near the river. Electrical methods have been used by many investigators to map silt and clay layers in alluvial aquifers of central and southern Arizona (Zohdy and others, 1974; Tucci and Pool, 1986; Anderson and others, 1992; Pool and Coes, 1999). Resistivity values range from about 7 to 15 ohm meters for saturated silt and clay layers and about 20 to 50 ohm meters (Pool and Coes, 1999) for saturated sand and gravel. Misidentification of conductive silt and clay layers with conductive ground water is unlikely because ground water in the area is commonly low in dissolved solids and has resistivity values of about 30 ohm meters.

Thirteen sites along a 25-km reach of the river were chosen for resistivity surveys (fig. 1) on the basis of geomorphology and proximity to existing or planned piezometers. Nine survey transects were oriented across the flood plain and roughly perpendicular to the river to determine if silt and clay layers in the basin fill are extensive beneath the Quaternary alluvium. Four transects were oriented parallel to the river for reasons of access. Transects extended to outcrops of basin-fill deposits on either side of the river where access permitted. Control for survey interpretation is available from aerial photographs, from which surface geologic contacts were derived, and lithologic logs of several wells, from which subsurface lithologic information was available. Borehole electromagnetic surveys are planned and will provide additional subsurface control.

Resistivity surveys were made using a Sting R1 IP/Swift earth resistivity meter[1] (Advanced Geosciences, Inc., Austin, TX). Sixty electrodes were spaced at 5- or 10- meter intervals for each survey. Additional 100-m roll-along surveys extended the lengths of surveys to as much as 1,520 m. The system was programmed to automatically sample the electrode array using Wenner or Schlumberger array electrode configurations. Apparent resistivity values generated by the surveys were inverted for the interpreted subsurface resistivity distribution using RES2DINV (Geotomo Software, Penang, Malaysia), a geoelectrical imaging software package, by minimizing the difference between observed apparent-resistivity data and synthetic apparent-resistivity data resulting from the modeled resistivity distribution.

Hydrogeologic Units

The primary regional aquifer that underlies the San Pedro River comprises Tertiary alluvial deposits of upper and lower basin fill (Pool and Coes, 1999). Secondary aquifers include Quaternary terrace and alluvial deposits that generally coincide with the flood plains of the San Pedro River and tributary streams. Tertiary pre-basin-fill sediments and Mesozoic and Paleozoic limestones that crop out in the mountains also are secondary aquifers in places. Other rocks that crop out in the mountains and hills surrounding the basin, including Tertiary and older granitic and volcanic rocks

[1] Use of firm, trade, and brand names in this report is for identification purposes only does not constitute endorsement by the U.S. Geological Survey.

and Mesozoic mudstone, quartzite, and conglomerate, are not known to be significant aquifers. Thickness of the regional aquifer near the river ranges from zero, where the river crosses crystalline and sedimentary rocks in the Tombstone Hills, to a few hundred meters (Gettings and Houser, 2000). Thickness of the Quaternary terrace and alluvial deposits along the river ranges from a few meters to as much as 15 meters.

Silt and clay layers in the basin fill and Quaternary alluvium can be distinguished from less electrically conductive sand and gravel layers using electrical methods. Silt and clay layers in the basin fill range from a few meters to tens of meters in thickness on the basis of geophysical logs and deep electrical soundings (Pool and Coes, 1999). Lakebed and cienega deposits occur in the Quaternary alluvium. The Quaternary alluvium also includes pre- and post-entrenchment alluvium (Hereford, 1993) that should have different electrical properties on the basis of lithology. Pre-entrenchment alluvium is primarily sand, silt, and cienega deposits that were deposited in a low-energy fluvial environment. The post-entrenchment alluvium is primarily sand and gravel that accumulated with the entrenchment of the river and subsequent lateral erosion during the last 100 years. The fine-grained deposits of the pre-entrenchment alluvium should be more electrically conductive than the coarse-grained post-entrenchment alluvium.

Survey Results

Results of 13 electrical-resistivity transects define 3 areas—north, middle and south—along the river that have different lithologic layering within the upper 50-100 m of the subsurface (fig. 1). The northern reach is defined by the four northernmost transects (fig. 1), which lack a conductive zone. The middle reach is defined by the middle seven transects, which include a distinct conductive layer (5-15 ohm meters) within the basin fill that thickens from north to south from a few meters to more than 20 m. The southern reach is defined by the southern two transects, which include a conductive layer (10-15 ohm meters) within the basin fill that extends to 100 m (the maximum depth of the surveys). The upper 15 m of each transect includes basin fill and Quaternary alluvium that have electrical-resistivity values ranging from 5 to 400 ohm meters. Post-entrenchment alluvium generally is more resistive than pre-entrenchment alluvium. Significant resistive zones also occur in the pre-entrenchment alluvium. The presence of theses zones suggests a more complex depositional environment, including significant high-energy deposits, than was previously thought. The water table is indistinguishable in most transects except where thicknesses of highly resistive and unsaturated basin-fill deposits exceed a few meters.

Transect A (fig 2), the northernmost transect, is typical of the northern reach. The survey included 60 electrodes at 10-m spacing. Data were collected using the Wenner array configuration. The survey extends almost completely across the flood plain from the base of basin-fill bluffs on the west to the San Pedro River on the east, which is about 50 m from basin-fill bluffs on the east side of the flood plain (fig. 2). The terrain is flat, and the land-surface elevation drops gradually about 3 m from the west end of the transect to the east end. Depth to water is about 4.6 m in a piezometer approximately 200 m from the west end of the transect and is less than 1 m near the river.

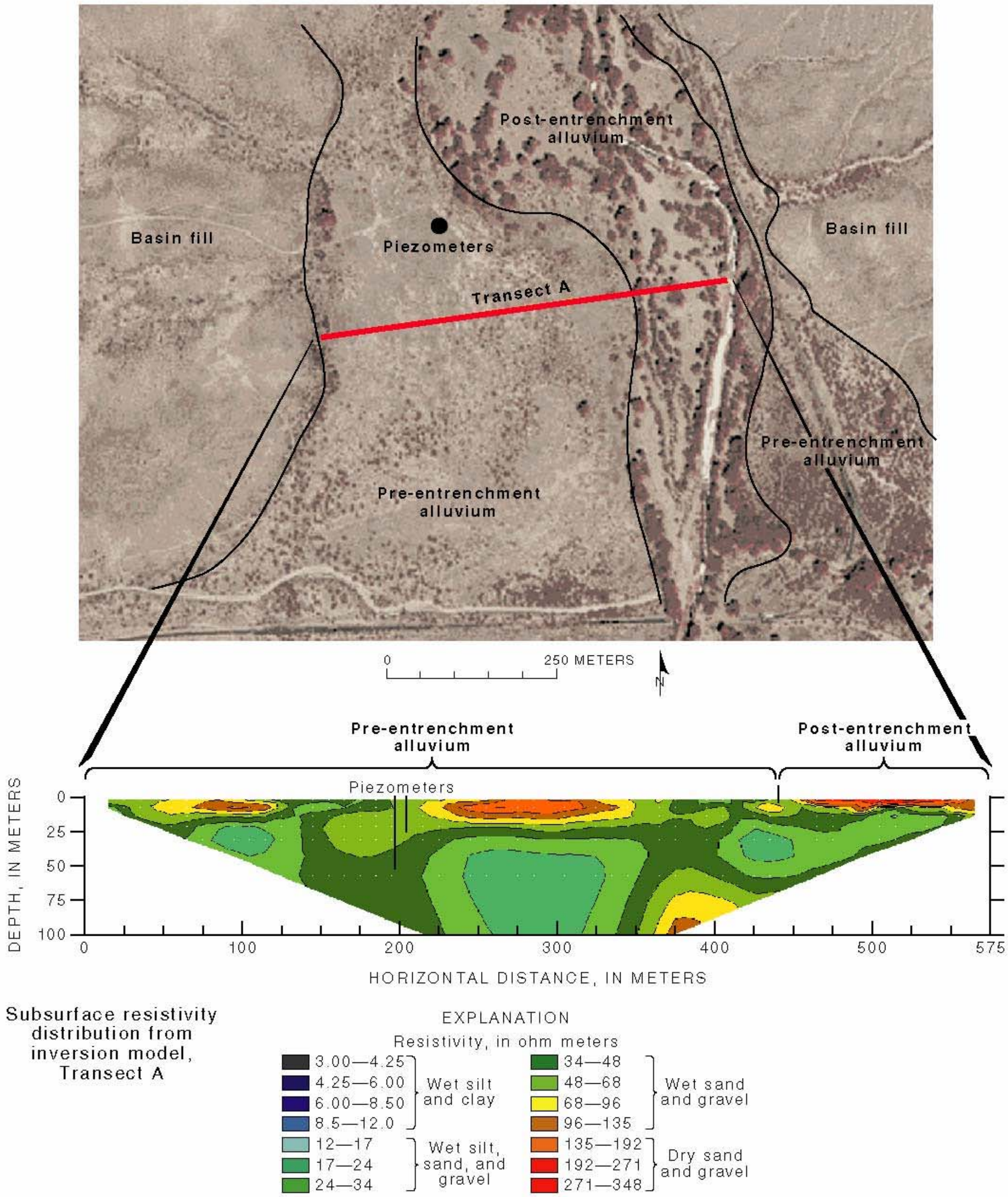

Figure 2. Resistivity transect A and inversion model results.

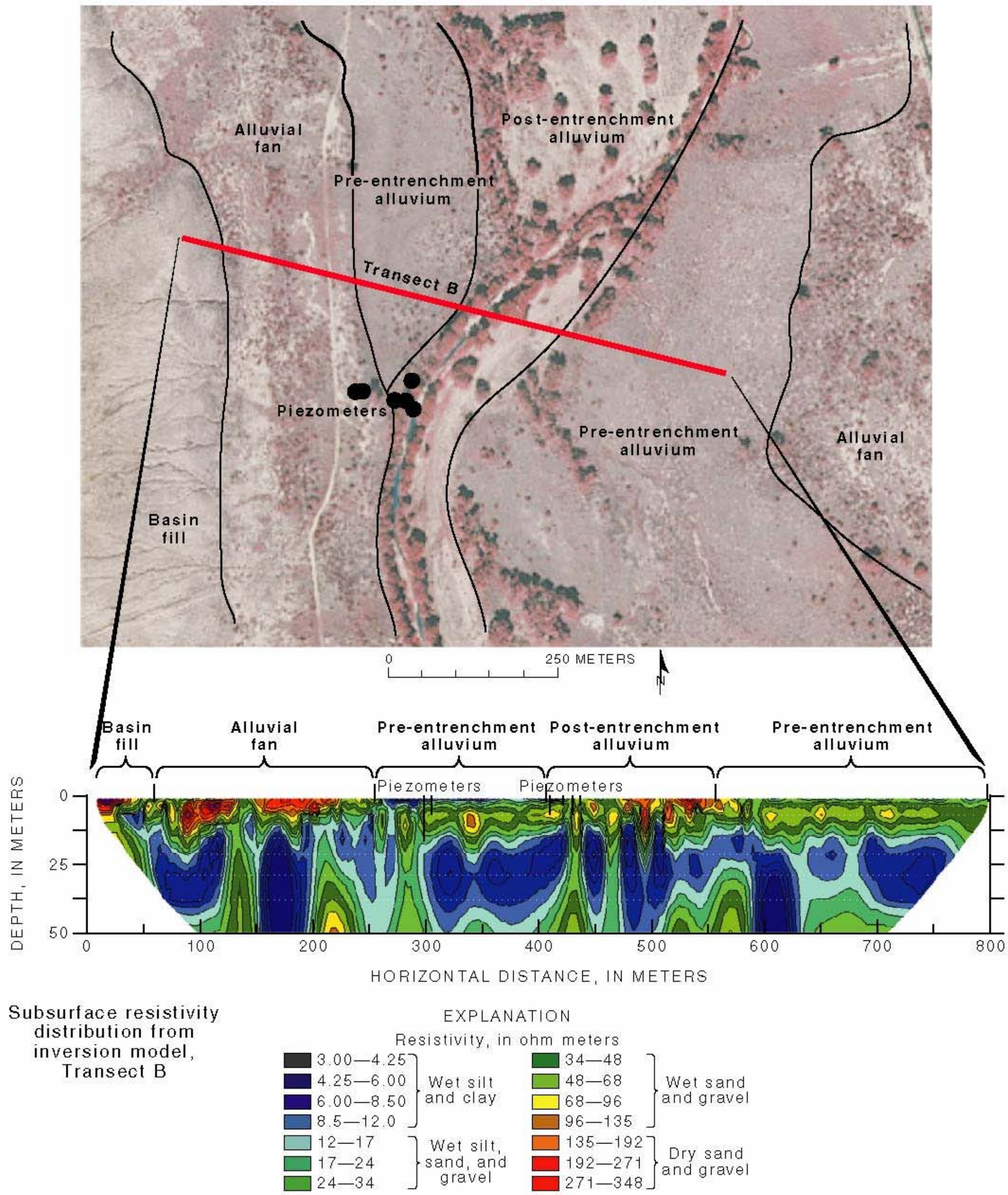

Figure 3. Resistivity transect B and inversion model results.

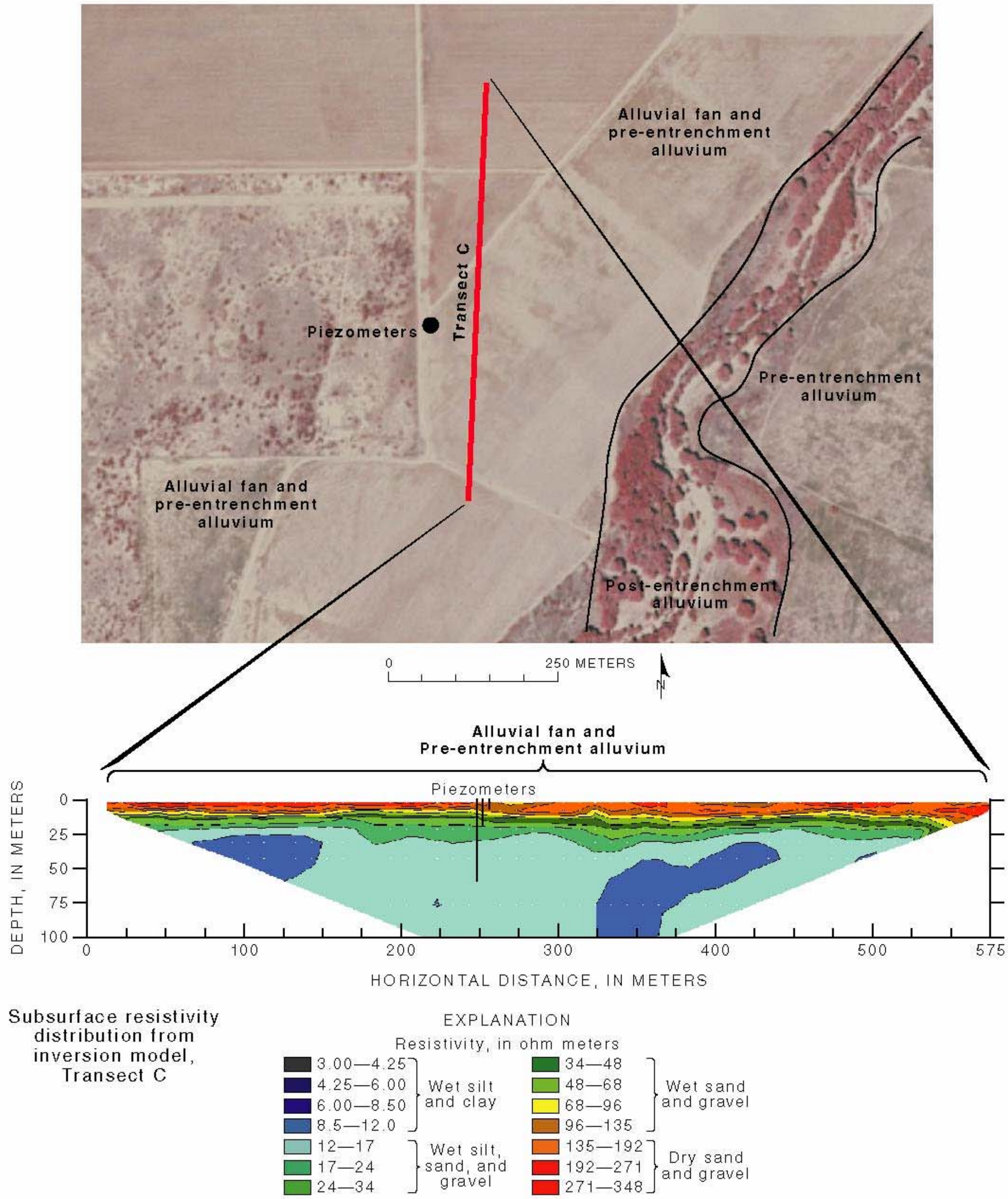

Figure 4. Resistivity transect C and inversion model results.

Inversion of the Wenner array data for transect A resulted in an average error of 2.5 percent between the observed and model apparent-resistivity values (fig. 2). The resistivity of the upper 15 m of the subsurface ranges from 24 to more than 300 ohm meters, which is indicative of sand and gravel deposits. These deposits likely are the stream alluvium and terrace deposits. The upper 5 to 7 m along the eastern 130 m of the transect includes resistive sand and gravel of the post-entrenchment alluvium. Other shallow resistive zones likely are sand and gravel deposits within the pre-entrenchment alluvium. Resistivity values for the basin fill generally range from 20 to 50 ohm meters, which indicate deposits of silty, clayey sand and gravel. Quaternary alluvium is difficult to distinguish from basin fill on the basis of resistivity data because the lithology of the two units is similar. The transect displays no apparent silt and clay zones that could significantly inhibit ground-water flow to the river.

Transect B (fig. 3) is typical of the middle reach, although the two southernmost transects show a transition to the southern reach. Transect B included electrodes at 5-m spacing. Data were collected using the Schlumberger array configuration. The transect included several roll-along surveys for a completed length of 795 m. The survey extends across the flood plain from the top of 10-m high bluffs of basin fill on the west, across the San Pedro River at 435 m, and onto the eastern part of the flood plain (fig. 3). Land surface below the bluffs gradually slopes downward about 3 m to a 1 m terrace at the river and then slopes upward 2 m to the east end of the transect. Depth to water is about 4 m in a piezometer south of the transect and west of the river and is zero at the river.

The Schlumberger array data for transect B included some poor data, and inversion results were relatively poor (average error of 13.2 percent; fig. 3). The transect, however, yields useful information regardless of the poor data. The upper 10 m of the subsurface has a large range of resistivity values—5 ohm meters to more than 300 ohm meters. The upper 3 m of the pre-entrenchment alluvium is conductive material (5 to 15 ohm meters) that correlates with cienega deposits of clay and silty sand found at piezometers about 100 m south of the transect (fig. 3). A more resistive layer, as high as 50 ohm meters, that probably is sand and gravel underlies the cienega deposits to a depth of about 10 m. Post-entrenchment deposits of resistive sand and gravel occur in the upper 3 m of the subsurface east of the river. Unsaturated basin fill deposits having resistivity values as large as about 400 ohm meters occur west of the bluffs. Resistivity values for saturated basin fill generally range from 5 to about 50 ohm meters and include a 20- to 30-m thick conductive zone (5 to 15 ohm meters) that underlies the entire transect.

The extensive conductive zone of basin fill at transect B likely is silt and clay that effectively separate the ground-water flow system into a deep system that is poorly connected to the river and a shallow system that is well connected. A poor hydraulic connection between the river and the deep flow system is evinced by water levels in several deep piezometers that are a few meters above the river level. The silt and clay layer restricts ground-water flow from the deep system to the river in this area. Most of the deep ground water flows downgradient to the north where the clay is absent and vertical flow to the river can more readily occur. Because water levels in wells completed above the silt and clay layer in the basin fill are below the river level, the river could potentially lose flow to the shallow system. The occurrence of the cienega deposits in the pre-entrenchment alluvium results in a complex shallow ground-water flow system. This interpretation is supported by water-level data in shallow piezometers.

Results of transect C (fig. 4) are typical of transects in the southern reach. This survey used electrodes at 10-m spacing. Data were collected using the Wenner array configuration.

This 590-m transect was oriented south to north in an abandoned agricultural field that sloped gradually upward to the north (fig. 4). Geology at this site is different from geology at the sites to the north. No basin-fill bluffs define the flood plain west of the river; however, basin fill does form bluffs east of the river. West of the river, the basin fill is overlain by alluvial fan deposits that apparently are contemporaneous with the pre-entrenchment alluvium. The transect does not extend onto the post-entrenchment alluvium, which lies below a 2-m high terrace west of the river. Depth to water is 5.8 m in piezometers approximately 240 m from the south end of the transect.

Inversion of the Wenner array data for transect C resulted in an average error of 2.0 percent between the observed and model apparent-resistivity values (fig. 4). The data generally resulted in a well-defined two-layer model. The upper 10 to 15 m is a uniformly resistive layer (50 to 200 ohm meters) that probably correlates with alluvial fan deposits. The low-resistivity (12 to 18 ohm meters) of the underlying basin fill indicates that the layer is predominantly silt and clay but is likely interspersed with sandy or gravelly zones that are too thin to resolve. Core and drill cuttings confirm the presence of sandy zones within a predominantly clayey matrix.

The hydraulic-head distribution in the wells adjacent to the transect and in other wells near the river indicate the potential for upward ground-water flow, and streamflow measurements indicate the river is gaining flow along this reach. Three piezometers near the transect are screened at depths of 59 to 61 m, 19 to 21 m, and 8 to 10 m. Multiple shallow piezometers near the river are screened at depths of 5 to 10 m. Water levels in the three piezometers near the transect are 2 to 4 m above the river level; the highest water level is in the deepest piezometer. Water levels in the shallow piezometers near the river are less than 0.3 m above the river level. Upward ground-water flow occurs, but is limited by the silt and clay layers. Poor vertical connection was documented by pump tests on a well near the river. Only the water level in the piezometer screened over the 19 to 21 m interval responded significantly to the pumping. The water level in the deep piezometer did not respond, but the water level in the shallow piezometer responded slowly.

Hydrogeologic Interpretation

The distribution of subsurface electrical properties along the river helps to explain observed hydrologic conditions. Figure 5 is a hydrogeologic section along the San Pedro River from south of Highway 92 to the Tombstone Hills. The section assimilates lithologic interpretations from the13 electrical-resistivity transects, water-level data from piezometers, and streamflow data. Ground water flows northward through the basin fill and discharges to the Quaternary alluvium or the river south of the Tombstone Hills. Discharge of ground water to the river is controlled in part by variation in the hydraulic conductivity of the aquifer and in aquifer thickness. Vertical flow of ground water is restricted in parts of the aquifer, such as the southern and middle reaches, that include thick silt and clay layers. This restriction limits ground-water discharge to the river and enhances horizontal ground-water flow to the northern reach where silt and clay layers are absent. Depth to bedrock along the section generally decreases in the direction of ground-water flow (Gettings and Houser, 2000). Where bedrock is shallow, such as in the northern reach, ground water is forced through a restricted aquifer thickness resulting in steep upward hydraulic gradients and enhanced discharge to the river.

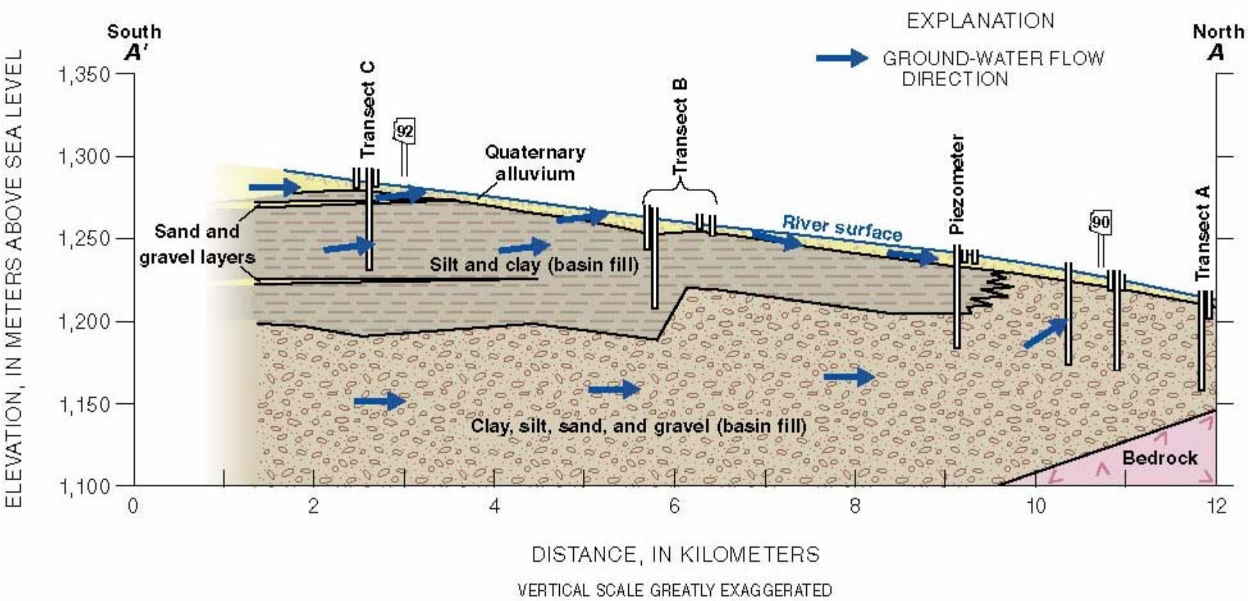

Figure 5. Hydrogeologic section along the San Pedro River.

Most ground water discharges to the river between Highway 90 and the Tombstone Hills, but some discharges along the southern reach and near Hereford in the middle reach. Upward ground-water flow and discharge to the river is inferred from piezometer data near Transect C. Discharge to the river near Hereford is inferred from historical streamflow data (Pool and Coes, 1999). Discharge to the river in these areas could have two causes. Ground water in permeable sand and gravel zones within the basin-fill silt and clay layers likely discharges to Quaternary alluvium at the erosional contact between the units. The relatively flat-lying sand and gravel layers within the basin fill are truncated by the Quaternary alluvium, which slopes at a low angle northward, following the grade of the river. Physical evidence of the truncation is provided by the presence of consolidated layers of basin fill that form the bed of the river near Highway 92. Secondly, ground water may discharge to the river near Hereford because of the restricted width of the Quaternary alluvium north of the area. South of Hereford, the Quaternary alluvium is broad and includes alluvial fan deposits west of the river. Near and north of Hereford, the Quaternary alluvium is restricted to a narrow zone that is 1 to 1.5 km wide between outcrops of basin fill.

On the basis of water-level data, ground-water flow in the Quaternary alluvium and flow in the river between Hereford and Highway 90 are effectively isolated from deep ground-water flow by the silt and clay layer. Water levels in deep piezometers completed in the basin fill are several meters above the river level. Upward ground-water flow must be minimal, however, because water levels in wells completed in the Quaternary alluvium in the area are below river stage. This relation suggests infiltration of river flow into the Quaternary alluvium. Accordingly, deep ground-water flow in the area must be primarily horizontal beneath the silt and clay.

Results of the electrical-resisitivity surveys in combination with water-level information from wells reveal important information about the source of water that discharges to the river and the distribution of wells in which ground-water withdrawals could divert flow to the two primary discharge areas along the river. Data enabled delineation of two discrete areas within which the regional aquifer contributes to streamflow in two discrete stream reaches. The divide between the two areas is near Hereford. Wells south of Hereford intercept ground-water flow to the river in the southern gaining reach of the river; although some deep wells may intercept flow that discharges to the river in the northern gaining reach. Wells north of Hereford will intercept ground-water flow to the northern gaining reach of the river.

Summary

Electrical-resistivity surveys were conducted near the San Pedro River to determine subsurface controls on the discharge of ground water to the river. The surveys yielded information on the distribution of silt and clay layers within the study area. Three river reaches were identified that have distinct subsurface distributions of silt and clay and streamflow characteristics. The northern reach has no significant silt and clay layers, and ground-water flows relatively unrestricted to discharge at the river. The middle reach has a significant silt and clay layer that effectively isolates the river and ground water in the Quaternary alluvium from a deep ground-water flow system in the basin fill. The southern reach has significant silt and clay layers that include interlayered sand and gravel that transmit a small amount of ground water to the Quaternary alluvium and river. Results enable delineation of two discrete areas within which the regional aquifer contributes to two discrete reaches of the river. The divide between the two areas is near Hereford. Wells south of Hereford will intercept ground-water flow to the river in the southern gaining reach; however, some deep wells may intercept flow that discharges to the river along the northern reach. Wells north of Hereford will intercept ground-water flow to the northern gaining reach of the river.

References

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